Transverse Splitting of Intense Heavy Ion Beams in the IRE and in an HIF Driver*

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MOTIVATION

For A Heavy Ion Power Plant Accelerator

The present driver design employs vacuum focusing of ~ 20 - 150 beams onto the target using magnetic quadrupoles and corrector magnets. Designs which transport a <u>small number of large beams</u>, or <u>high charge state beams</u> are not presently viable because such beams cannot be focused, due to space charge and aberrations that are too large to allow a good focus. These designs could be useful if either:

neutralized focusing
or
beam splitting

could be performed without a large increase in perpendicular temperature (i.e., emittance increase).

For The Next Large Accelerator Experiment

Two main goals for the IRE are:

1. Test beam transport and acceleration at full scale

   Full scale implies:

High current, high power beams	beam loading effect of particles hitting wall
Full size	engineering with proper tolerances

2. Target physics which cannot be tested by the NIF

   ion direct drive
   beam-target interaction

These two goals inherently conflict because of the low kinetic energy of the experiment compared to the driver.

Scaling comes from:

$$a'' = -Ka + \frac{\varepsilon^2}{a^3} + \frac{Q}{a+b} \qquad \text{(beam envelope equation)}$$

where

$$K = \frac{B'}{mc\beta\gamma} \qquad \text{(focusing term)}$$

$$a, b = \text{beam radii in x and y}$$

$$Q = \frac{1}{\pi\varepsilon_0} \frac{\lambda}{m_0 c^2 \beta^2 \gamma^3} \qquad \text{(Space charge term)}$$

$$\lambda = \text{charge per unit length}$$

$$\varepsilon = \text{emittance} = \frac{\varepsilon_n}{\beta\gamma} = \text{2D phasespace area}$$

As energy increases, space charge becomes less important. At the final focus, if we assume some limiting magnetic field for focusing which is the same for the IRE and the driver, then

$$\frac{Q}{a+b} \div Ka \qquad \beta^{-1}$$

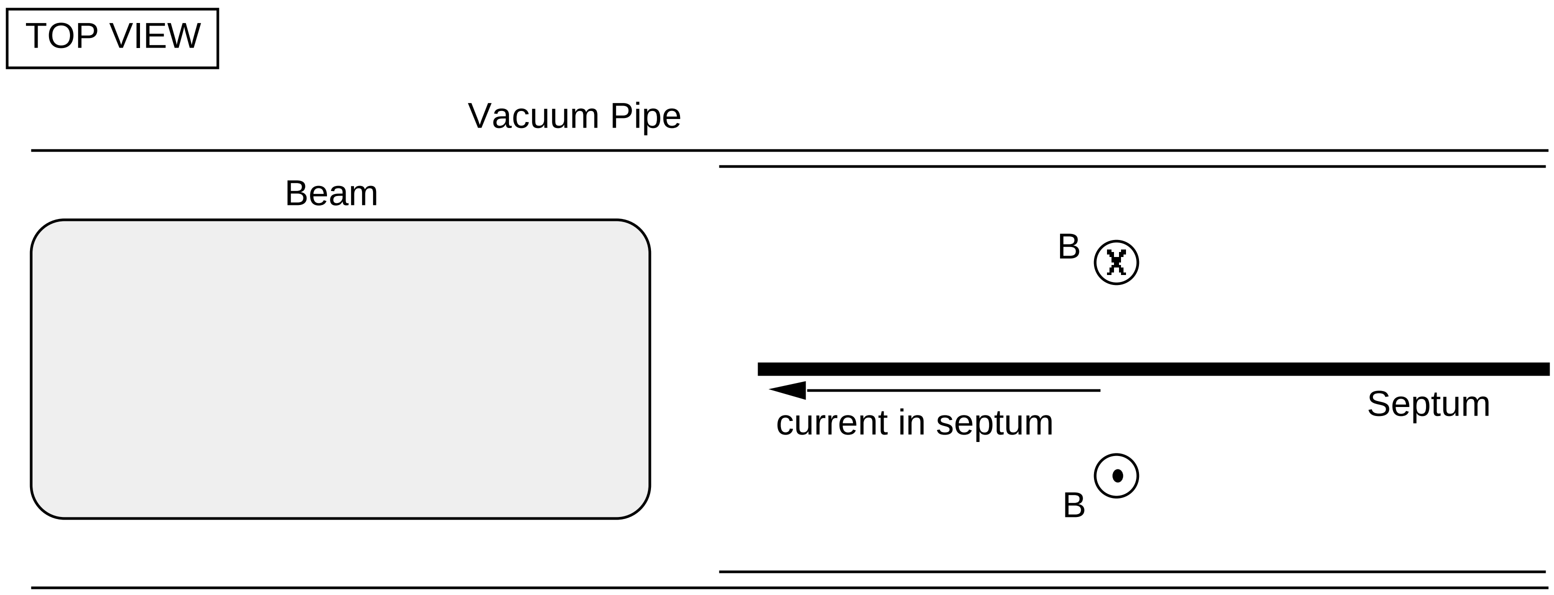
Space charge is proportionally too large in low energy experiment, compared to the driver. Transport will be tested properly, but drift compression and final focus need lower current.

Splitting beams provides:

more beams (for more symmetry on target, for instance)

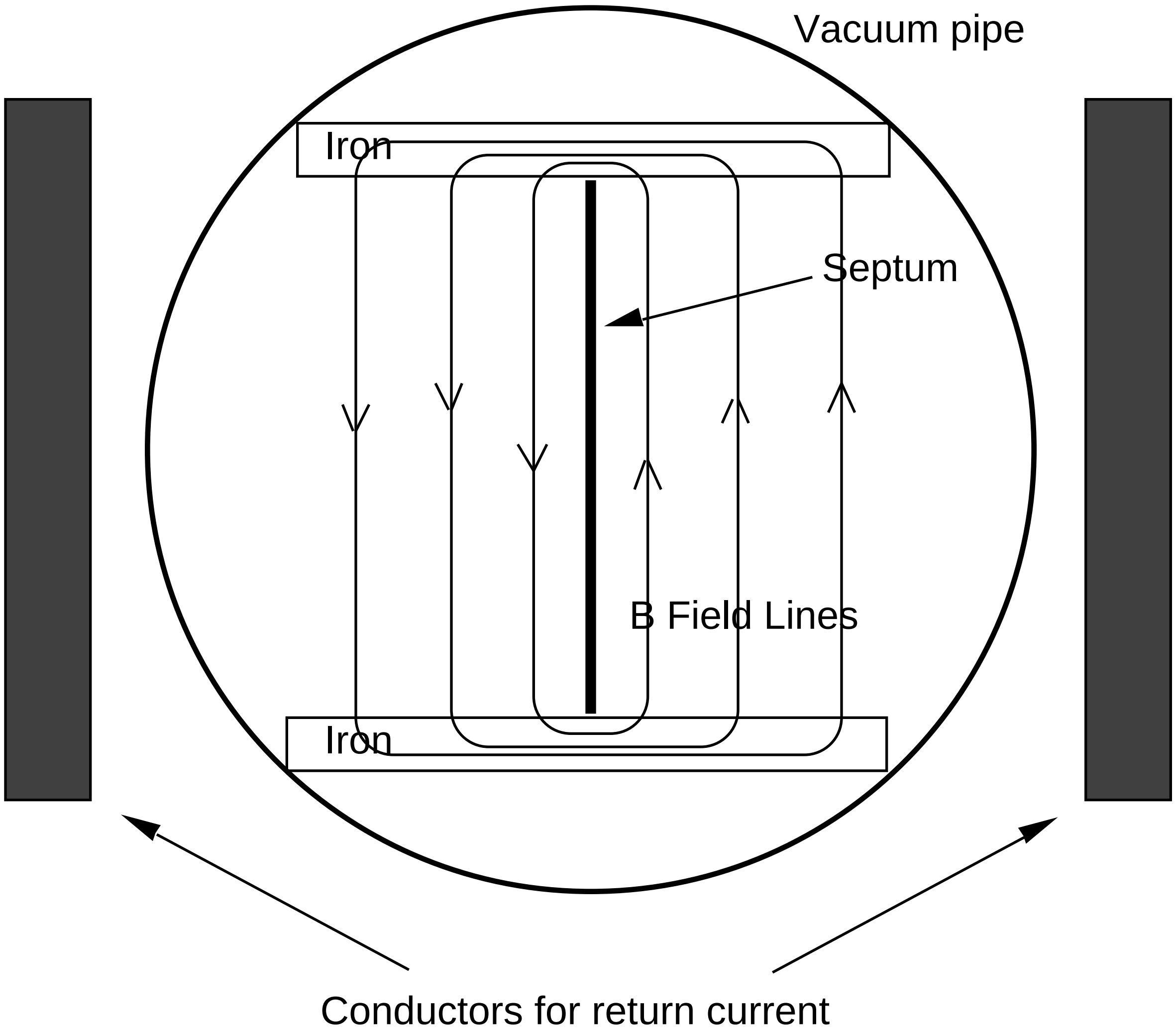
focusable beams

A Magnetic Septum to Split the IRE Beam Transversely



Current running parallel to the beam velocity through a thin sheet (~1 mm wide) of conductor (assumed below to be copper) creates dipole magnetic fields of opposite signs on either side of the sheet, or septum. The dipole fields separate the beam into 2 beams, which, when they are far enough apart, enter separate focusing channels.

End View


Vacuum pipe
Iron
Septum
B Field Lines
Iron
Conductors for return current

<u>Questions and Challenges for Splitting</u>

1. Will the resulting distribution function focus correctly?
2. How much beam will be lost?
3. Will the beam destroy the septum?
4. Will the septum overheat due to i^2R losses?
5. Is the power supply credible?
6. Will ions sputtered by the head of the beam destroy the beam tail?
7. What will be the result of electrons coming off the septum into the beam?
8. Would the pumpout time for sputtered ions limit the machine rep rate?
9. Is the cost of the system reasonable?

Answers to questions 2 - 6 are given below.

We have begun to answer question 1, using 2-D PIC simulations with the WARP code (Grote and Friedman).

Questions 7 and 8 have not been addressed here.

Some indication is given in the estimates below that power supply cost will be large, but the cost of the whole system (Question 9) is as yet uncalculated.

Estimate of Septum Current and Resistive Heating

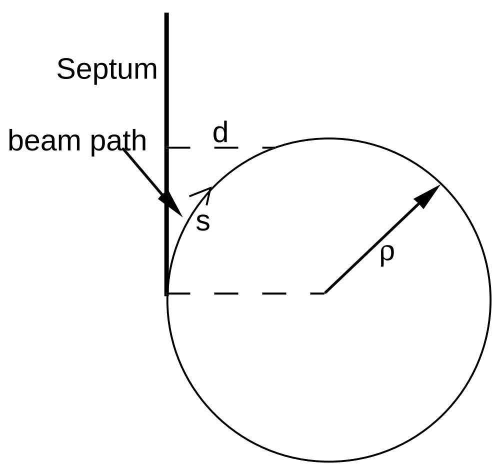
What dipole field strength is required?

Assume we need to separate the two beam centroids by 5 cm before they can enter separate focusing systems.

The path of the beam centroid in a perfect dipole field is given by:

$$\mathbf{d} = \rho - \rho \cos\left(\frac{\mathbf{s}}{\rho}\right) \approx \frac{\mathbf{1}}{\mathbf{2}}\,\frac{\mathbf{s}^2}{\rho}$$

(See diagram below for definition of symbols.)



Meanwhile, the beam space charge is expanding the beam. We neglect image forces in this estimate. The radius as a function of path length, s, is approximately

$$\mathbf{r}^2 \approx \mathbf{K}\mathbf{s}^2 + \mathbf{r}_0^{\,2}$$

assuming $\frac{r-r_0}{r_0}$<<1. Here K=$\frac{\lambda}{2\,\pi\epsilon_0\,\mathrm{mv}^2}$ is the perveance, with λ=charge per unit length, and r_0 is the initial beam radius.

So

$$\mathbf{r} - \mathbf{r}_0 \approx \frac{\mathbf{1}}{\mathbf{2}}\,\mathbf{K}\,\frac{\mathbf{s}^2}{\mathbf{r}_0}\,.$$

Using these 2 equations, the separation of the beam edges, Δ, is

Circuit to Drive Septum Current

We need approximately **100 kA** to produce the dipole field needed (~ 1 Tesla). We will get this current by discharging a capacitor through the inductance made by the vacuum chambers on each side of the septum.

Calculate the inductance :

$$L = \frac{\mu\, A}{l};$$

$$\mu = 4\, Pi * 10^{-7};$$

$$A = 12 * 10^{-2} * 1.0;$$

$$l = 12 * 10^{-2};$$

```
L // N
```

$$1.25664 \times 10^{-6}$$

Inductance of the vacuum chambers is 1.3 μH.

Calculate circuit parameters to drive a 500 μs half-sine pulse :

τ is the duration of the half-sine pulse.

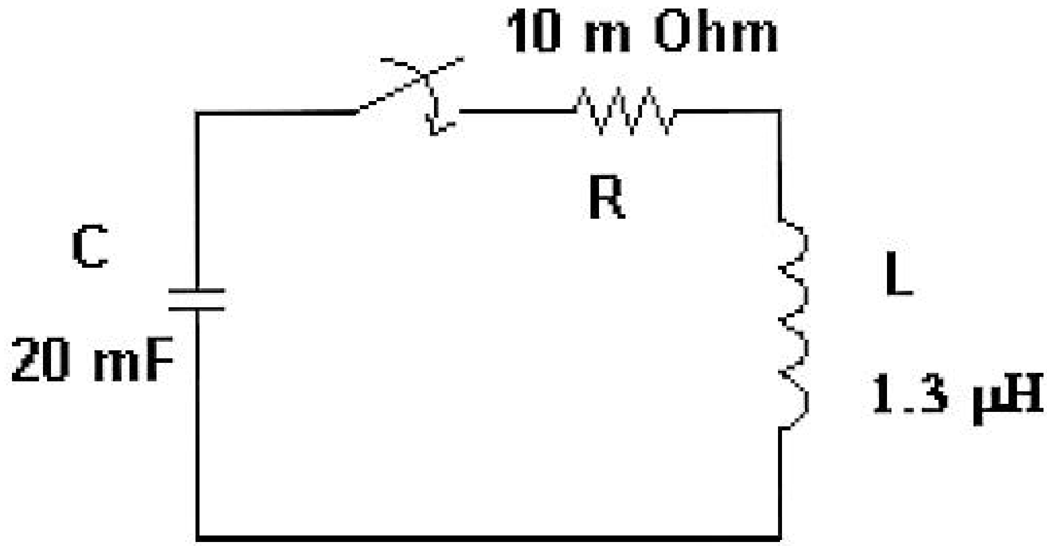
$$\tau = 500 * 10^{-6};$$

Calculate the resistance of the septum. $R = \frac{\text{septum length}}{\sigma * \text{septum cross sectional area}}$, where σ is the conductivity of the septum, assumed to be copper. The skin depth of copper for a 100 μs pulse is 0.66 mm, so at this frequency the skin depth, δ, is:

$$\delta = 0.66 * 10^{-3} * \sqrt{\frac{\tau}{50 * 10^{-6}}}$$

$$0.0020871$$

The skin depth is larger than the assumed width of the septum, so the width of the septum is used as the area through which the current passes.


10 m Ohm
R
C
20 mF
L
1.3 μH

$$R = \frac{1.0}{(5.9 * 10^7) * (12 * 10^{-2}) * (1 * 10^{-3})}$$

0.000141243

This resistance will be small compared to that of the cables, etc. **Assume R=10 mΩ.**, which is in the ballpark of the contribution from the cables, connections, power supply, etc.

R = 0.01;

$$\sqrt{\frac{1}{L\,C} - \frac{R^2}{4\,L^2}}\ \tau = \pi$$

$$Cap = 1.0 \Big/ \left(L * \left(\frac{Pi}{\tau}\right)^2 + \frac{R^2}{4\,L}\right)$$

0.0201556

The capacitor needed is a 20 mF capacitor.

$$Z = \sqrt{\frac{L}{Cap} - \frac{R^2}{4.0}}$$

0.00789568

The impedance is 7.9 mΩ. The effect of the resistance on the impedance is small.

$$ZLC = \sqrt{\frac{L}{Cap}}$$

0.007896

<u>Calculate the voltage required</u>:

i = 100000;

V = i Z

789.568

The voltage required is 790 V. With a pulse length of 500 μs, this can be supplied using a solid state thyristor-driven power supply.

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Find the power dissipated:

$$P = i^2 R / 2$$

$5. \times 10^7$

$$\text{energy} = P\,\tau$$

25000.

The energy dissipated per pulse is 25 kJ. This is heat in the cables-- the losses in the septum are 2 orders of magnitude lower. With this amount of heat, the cables can be air-cooled for rep rates ~ 1 Hz, or water-cooled for higher rep rates.

The large power also raises cost issues, which will have to be settled when more of this research is completed and the benefits of splitting are more clear.

$$\Delta \approx \frac{s^2}{\rho} - K \frac{s^2}{r_0}$$

giving

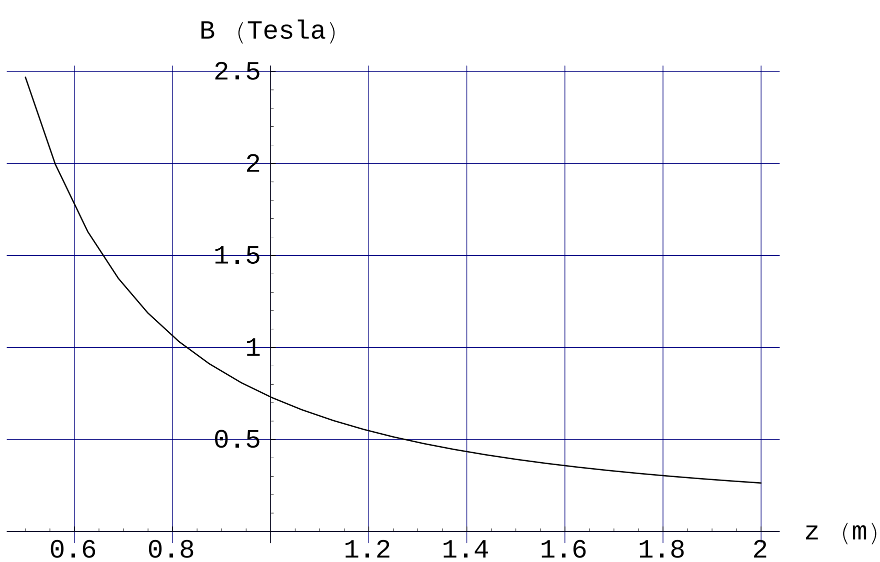
$$\rho \approx \frac{s^2}{\Delta + Ks^2 / r_0}$$

$$B \approx \frac{mc}{q} \beta \frac{\Delta + Ks^2 / r_0}{s^2}.$$

s=length of septum
K=perveance
r_0=beam radius at beginning of splitting
Δ=desired separation of beam edges at end of septum

Plot B required vs. length of the septum, for possible IRE parameters:

r_{0x}=1.72 cm (2 x rms radius after split)
K=2.52 x 10^{-4}
Δ=5 cm
K^+ ions at 200 MeV.



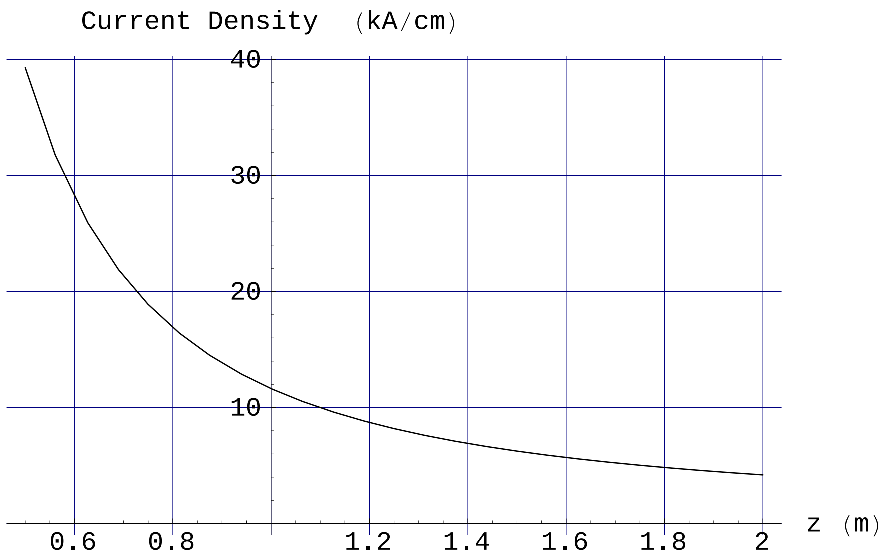
So if we want to separate the beams in ~1 meter, so that the effect of beam space charge is minimal, we need

B~0.7 Tesla.

For B=1 T, the septum will be about 0.8 m long, and 0.55 m for 2 Tesla.

Septum current needed:

Estimating the current using the B of an infinite current sheet gives:



So for a septum of height 12 cm and length 1 m, we need

i≈130 kA.

Power Dissipated in the Septum:

We assume a copper septum. The conductivity of copper is 5.9 x $10^7 \text{ohm}^{-1} m^{-1}$.

$$P = i^2 R$$

$$R = \frac{\text{septum length}}{(5.9 \times 10^7)\ (\text{septum area})}$$

$$= 0.14\ \text{m}\Omega$$

$$P \approx 2\ \text{MW}$$

For a 500 μs pulse, this is

1 kJ per pulse.

Calculate the temperature rise of the copper for 1 pulse for the parameters used above, i.e.,

length = 1 m
height = 12 cm
width = 1 mm.

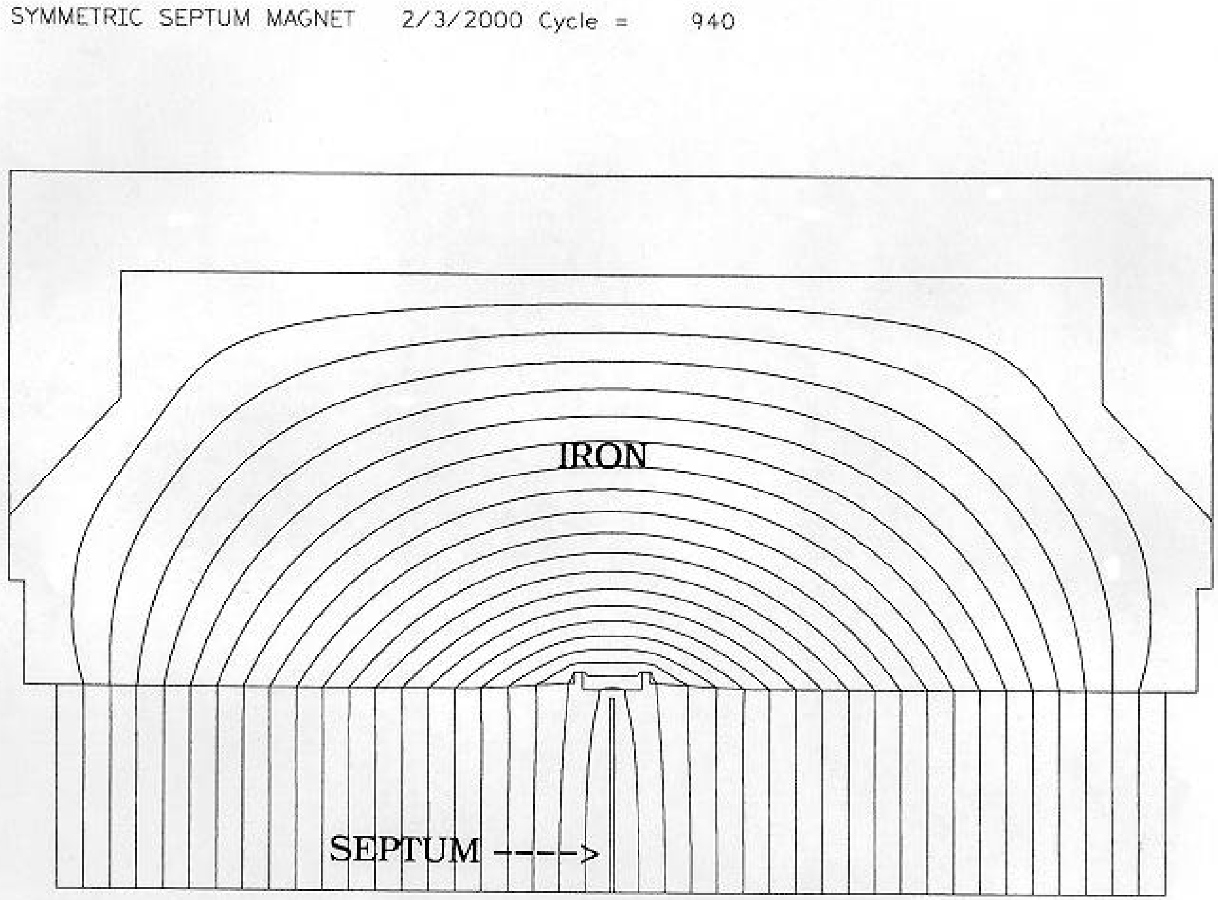
Using the specific heat of copper (0.093 cal/gm-°C), we find

$$\Delta T = 2.33\ °C$$

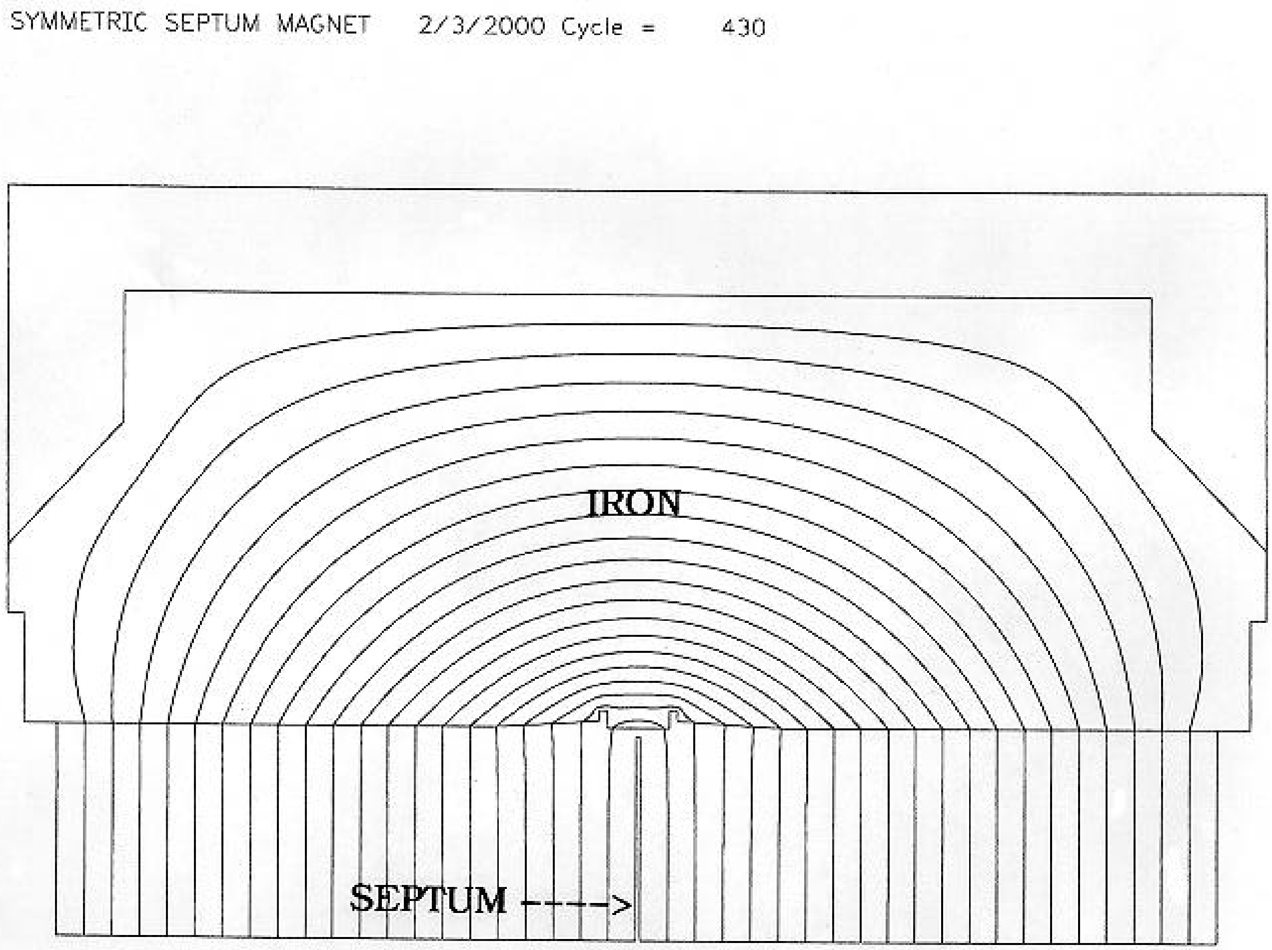
for a single pulse. The temperature rise is insignificant.

POISSON calculations show that iron at the top and bottom of the transport channel will shape the field and keep it from reconnecting through the septum, thus maintaining field quality.

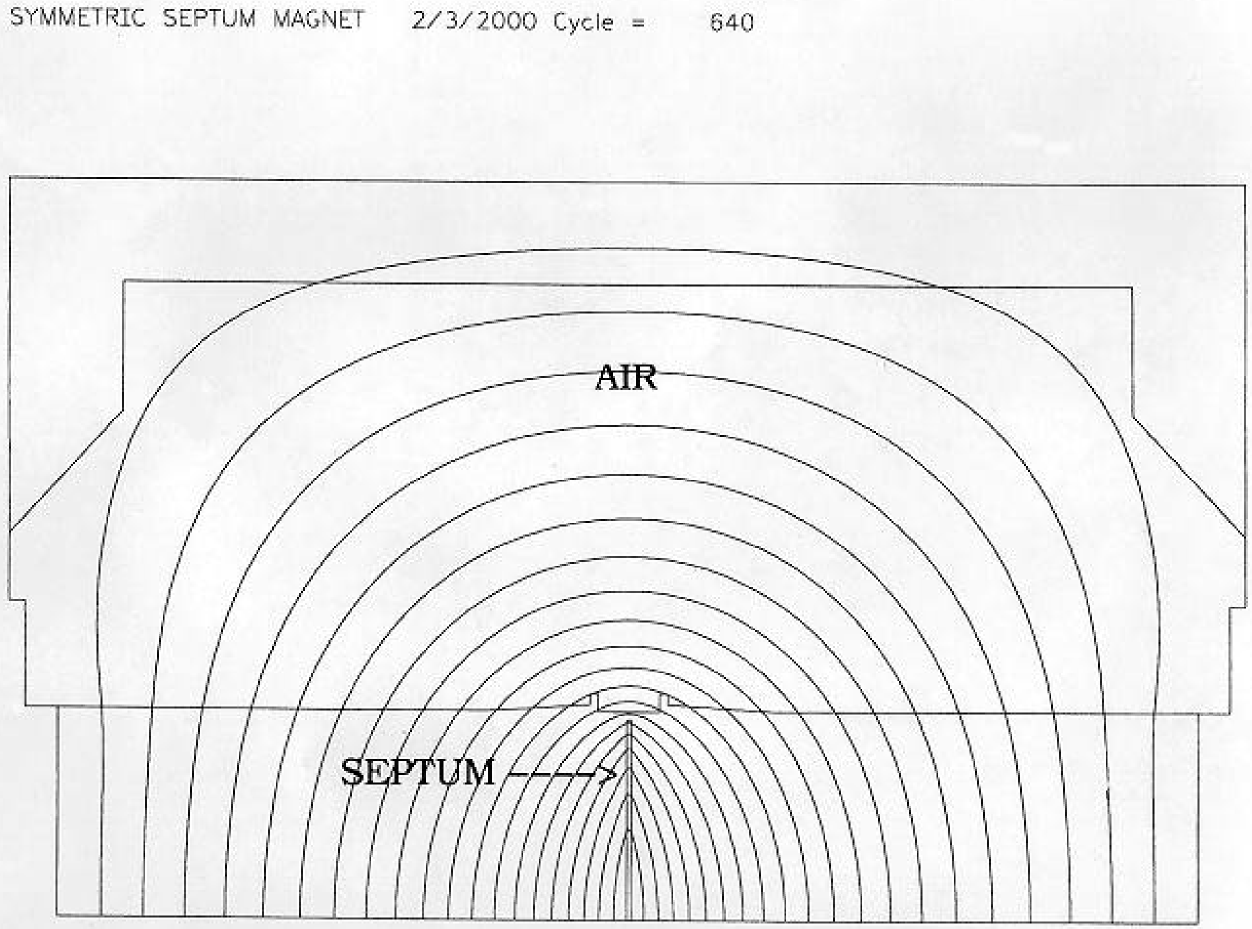
WITH IRON   T=INFINITY



WITH IRON T=0



NO IRON T=INFINITY



Energy Deposited on the Septum

IRE beam:

200 MeV of K^+ = 5.13 MeV/nucleon
radius ≈ 4 cm
number of ions/beam = 4.5 x 10^{13}

So **313 kJ/m²** is deposited by the beam on the septum in ~ 5 - 20 ns.

Range (see graph) in copper is ≈ 11.6 mg/cm² 13 μm depth **24 kJ/cm³ deposited!**

In copper, this is 1.8 eV/atom, which is close to what is needed for sputtering. 8 kJ/cm³ melts the copper, if it is initially at 20°C.

Beam must not hit the septum-- it will destroy it. Must hit a thin layer of expendable material (gas or liquid jet? thin wire?)-- a "pseudoseptum". Depth of material required is ~ tens of μm.

For a driver:

Beams are at 3 - 10 GeV, but atomic mass is larger MeV/nucleon about 3 x higher than the IRE. Then the range is about 1.4 x range of IRE beams. So energy deposited is about 3.3 times higher.
Same conclusions are true as above.

Beam Loss

Assume width of pseudoseptum = 1 mm, and beam is round.

Then **1.25%** of the beam is intercepted. This can be made smaller by expanding the beam.

Beam loss is small

"Black cloud" effect:

Particles sputtered off the pseudoseptum can intercept beam ions and destroy the beam by charge-exchange. Sputtering data seems to indicate ~ 1 ion sputtered for each beam ion.

But in 5 - 20 ns, ions don't go far-- a fraction of a mm, in force-free environment. Here they are also repelled by the beam, so

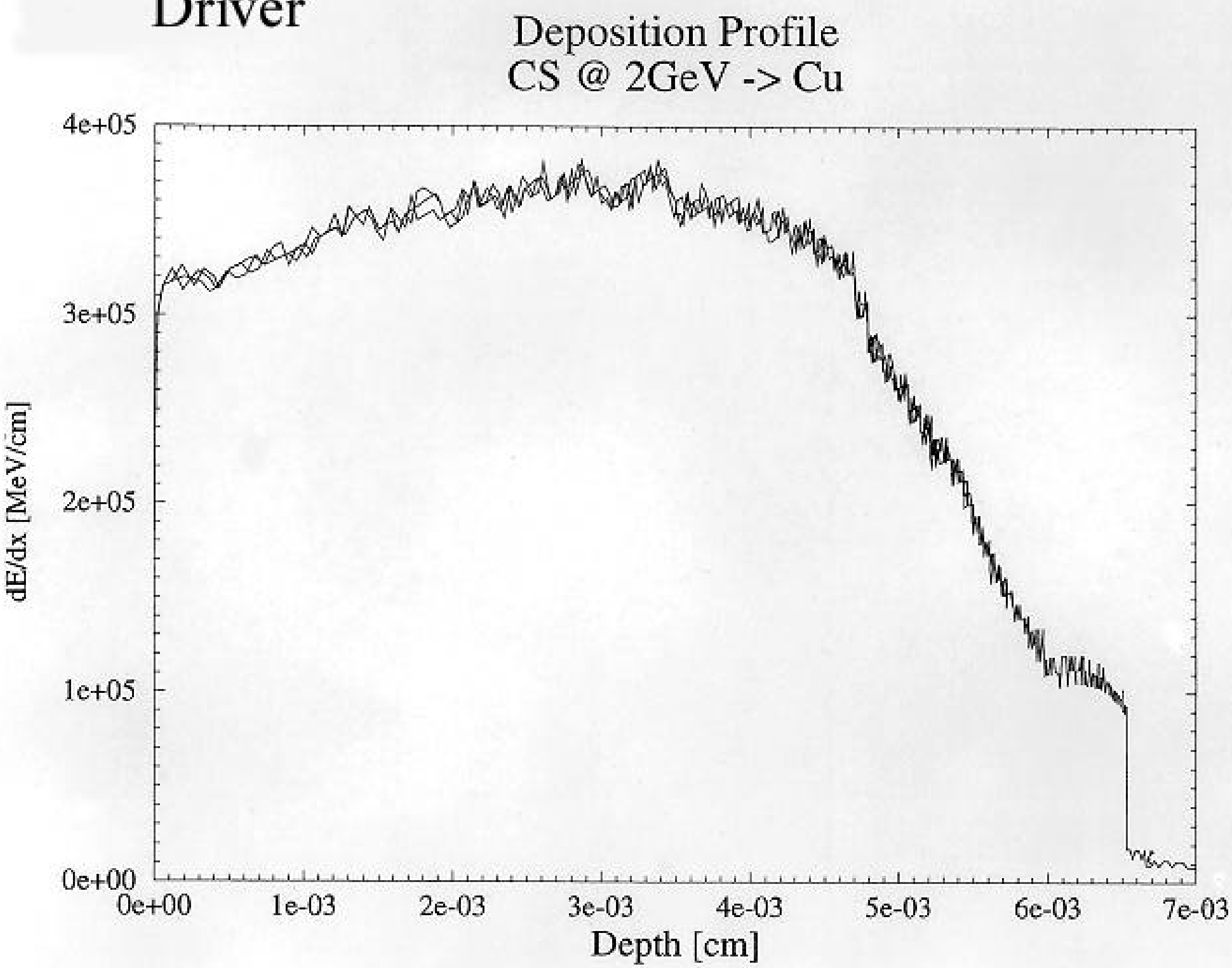
Beam loss from sputtered ions is expected to be a small fraction of a percent

Electrons:

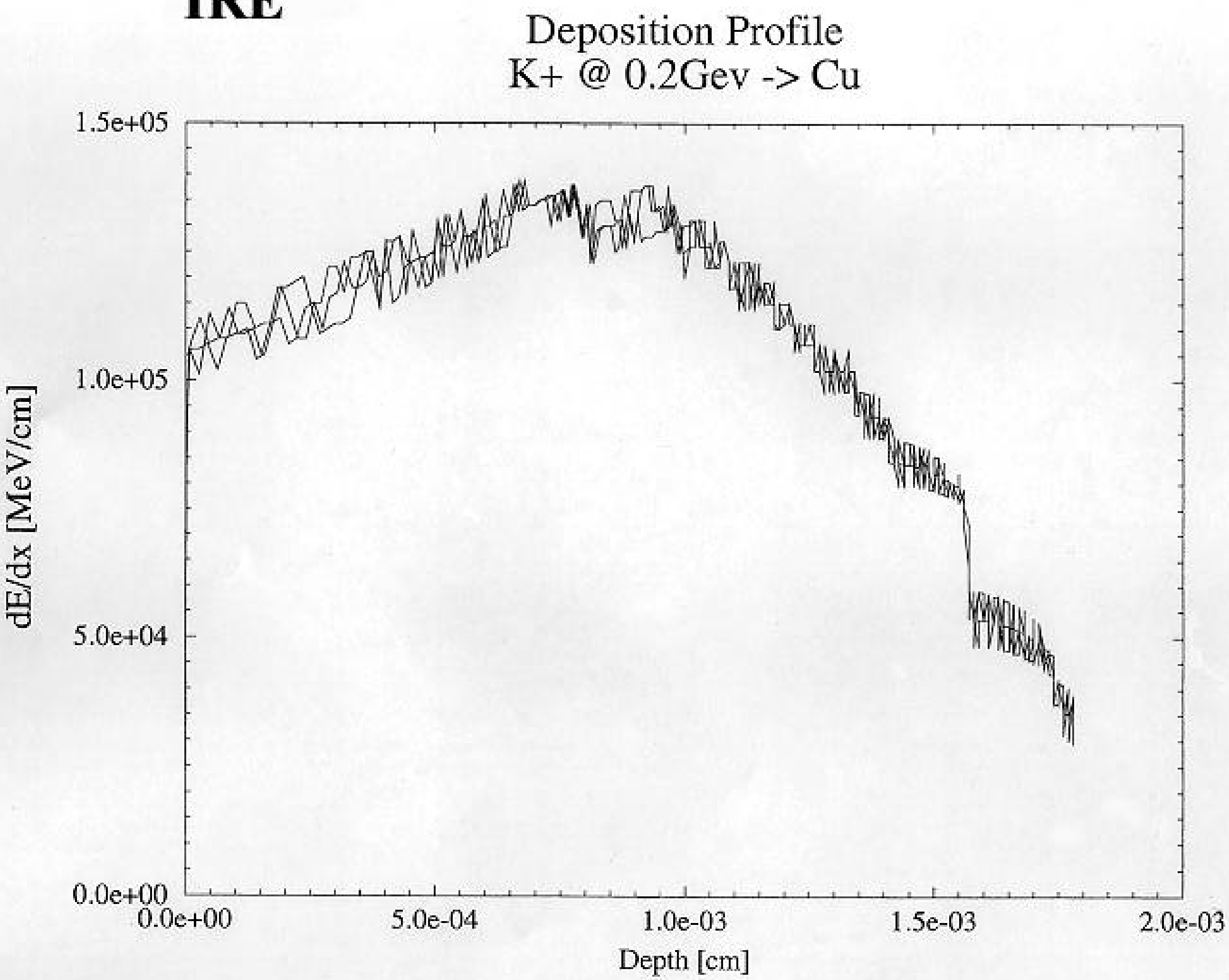
Electrons also come off the pseudoseptum into the center of the beam. They will be ripped out by the beam potential of the head of the beam before the beam arrives, and accelerated toward the beam. They should be confined along magnetic field lines. Clearing electrodes might also be used to confine them to the immediate vicinity of the septum. But the neutralization caused by the electrons and its effect on the beam is a complicated problem which deserves the attention of numerical simulation.

The effect of electrons needs careful further study. If important, it can probably be handled by using clearing electrodes in the septum area, where the electrons are still at the beam edges.

Driver


Deposition Profile
CS @ 2GeV -> Cu
dE/dx [MeV/cm]
4e+05
3e+05
2e+05
1e+05
0e+00
0e+00
1e-03
2e-03
3e-03
4e-03
5e-03
6e-03
7e-03
Depth [cm]

IRE



Deposition Profile
K+ @ 0.2Gev -> Cu
dE/dx [MeV/cm]
1.5e+05
1.0e+05
5.0e+04
0.0e+00
0.0e+00
5.0e-04
1.0e-03
1.5e-03
2.0e-03
Depth [cm]

These range calculations were made using the code ZSTOP, written by Scott Armel (U. C. Berkeley and LBNL). ZSTOP incorporates a dynamic charge evolution model into a stopping power calculation. The stripping cross sections used are condition-dependent, selecting from among the Bohr, Bethe or Binary Encounter models. A probabilistic accounting for multiple-electron effects is used following the work of Meyerhof et. al [1]. The stopping power employs either the Bohr or Bethe logarithm following the analysis of Sigmund[2]. Modeling for atomic electron distribution were taken from Chen et. al [3] and the inner electron binding energies were scaled using atomic screening constants.

[1] W. E. Meyerhof et al., Physical Review A, 35 #4, Feb. 15, 1987 p1967.
[2] P. Sigmund, Physical Review A, 56 #5, November 1997, p3781.
[3] Y.F. Chen et al., J. Phys. B, 26 (1993), pp1071-1080.

Input Parameters for IRE PIC Runs

Runs were done with the 2D version of the particle-in-cell code WARP
(D. Grote and A. Friedman).

Septum:

$0 \leq z \leq 0.541$ m
height = 20 cm
width = 1 mm
B = 2 T

Fields are perfect dipole fields. No fringe fields.
Septum is perfectly conducting grounded sheet.

Beam:

The code assumes that an elliptical beam with initial radii of 4.6 and 2.3 cm has been split into 2. It follows one semicircular half-beam starting at the beginning of the septum.

ion = K^+
λ = 5.15 μC/m
K = 2.52 x 10^{-4} (perveance)
kinetic energy = 200 MeV
initial normalized emittances = 2.5 mm-mrad (x)
5.0 mm-mrad (y)

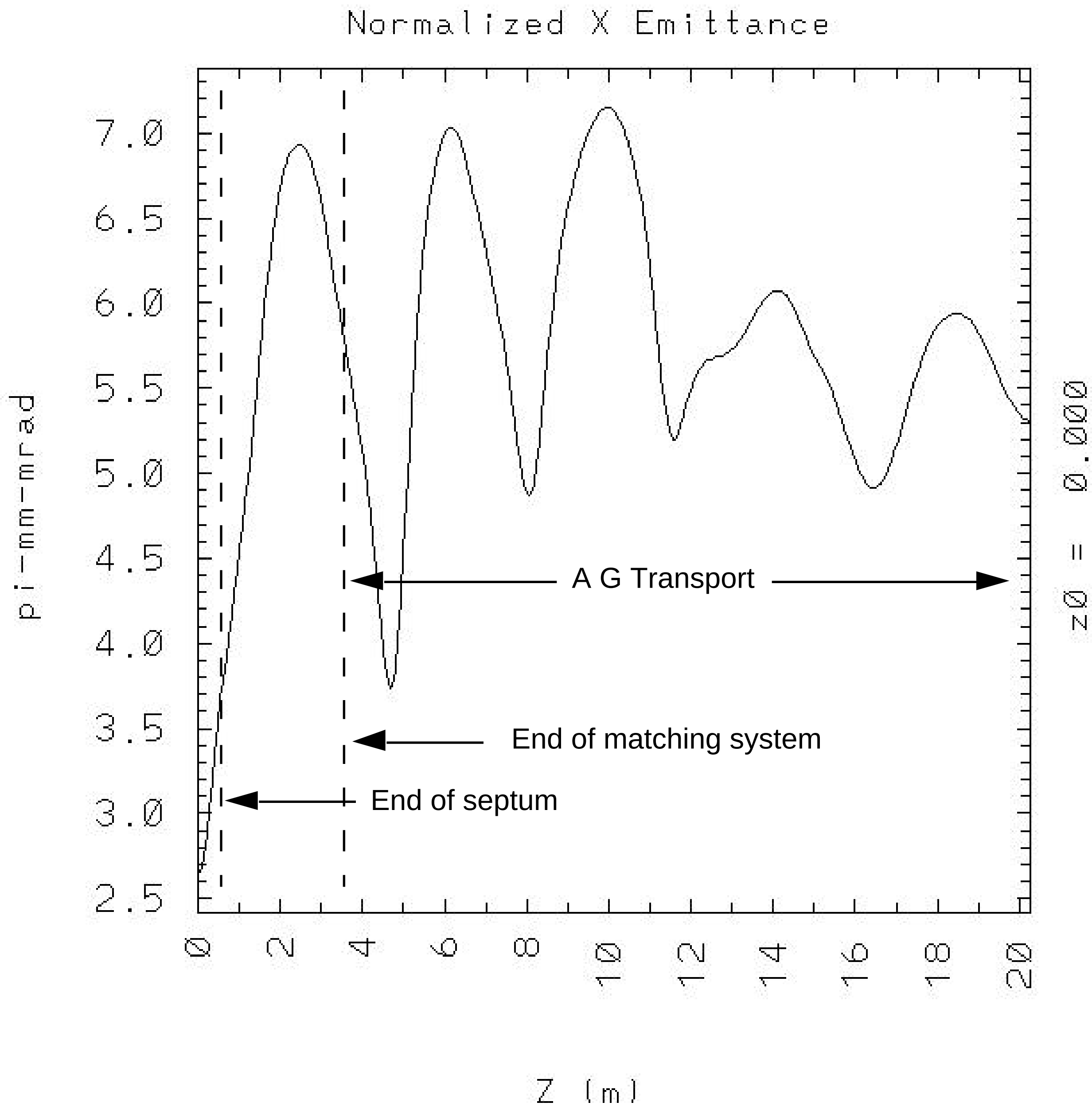
Matching Section:

Matches the beam envelope radius and angles to the downstream alternating-gradient focusing system. Consists of 4 quadrupoles.

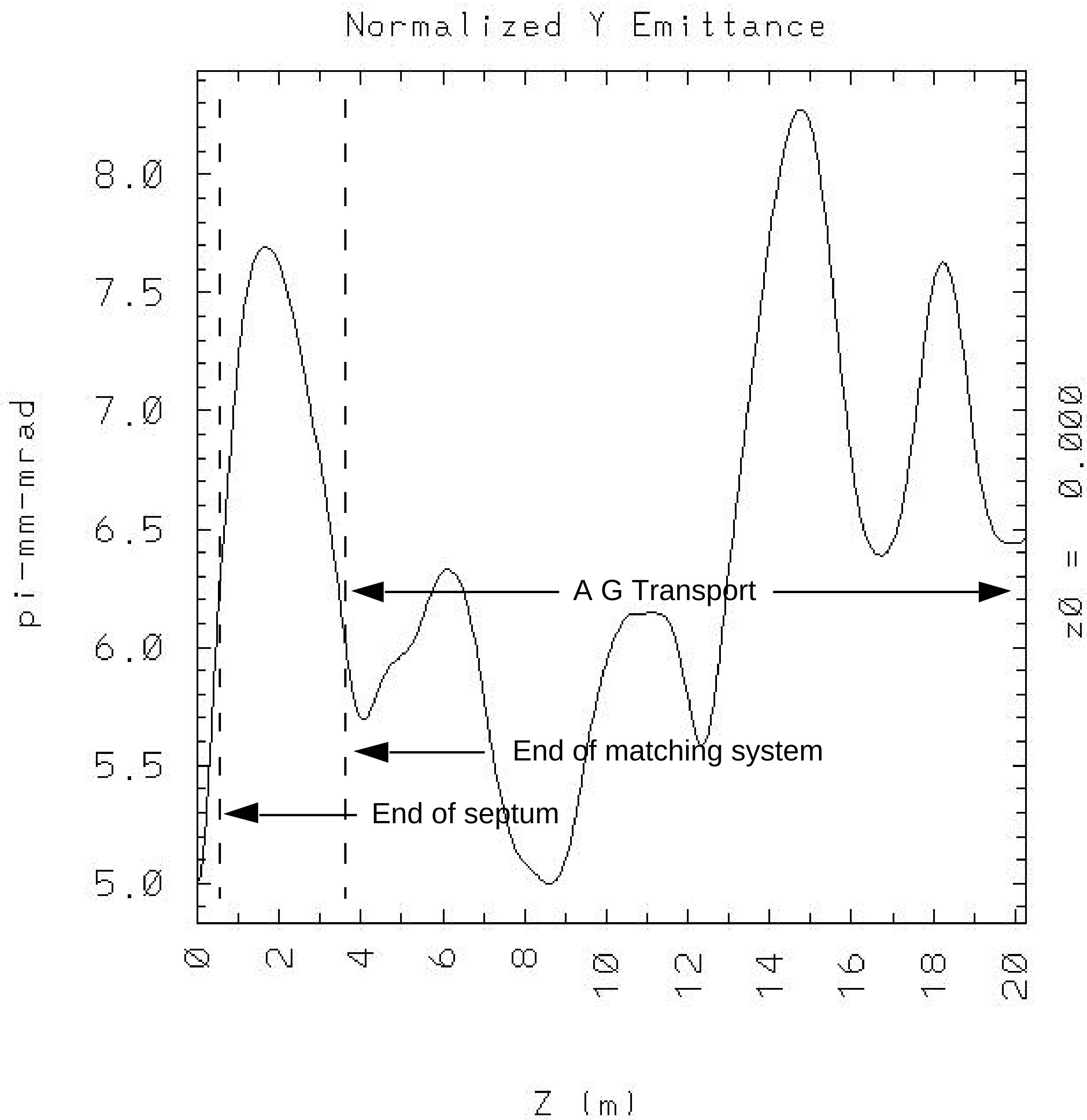
quadrupole lengths: 0.21, 0.42, 0.42, and 0.42 m
half-period (distance between quadrupole centers) = 0.844 m

Alternating Gradient Focusing Lattice after Matching Section:

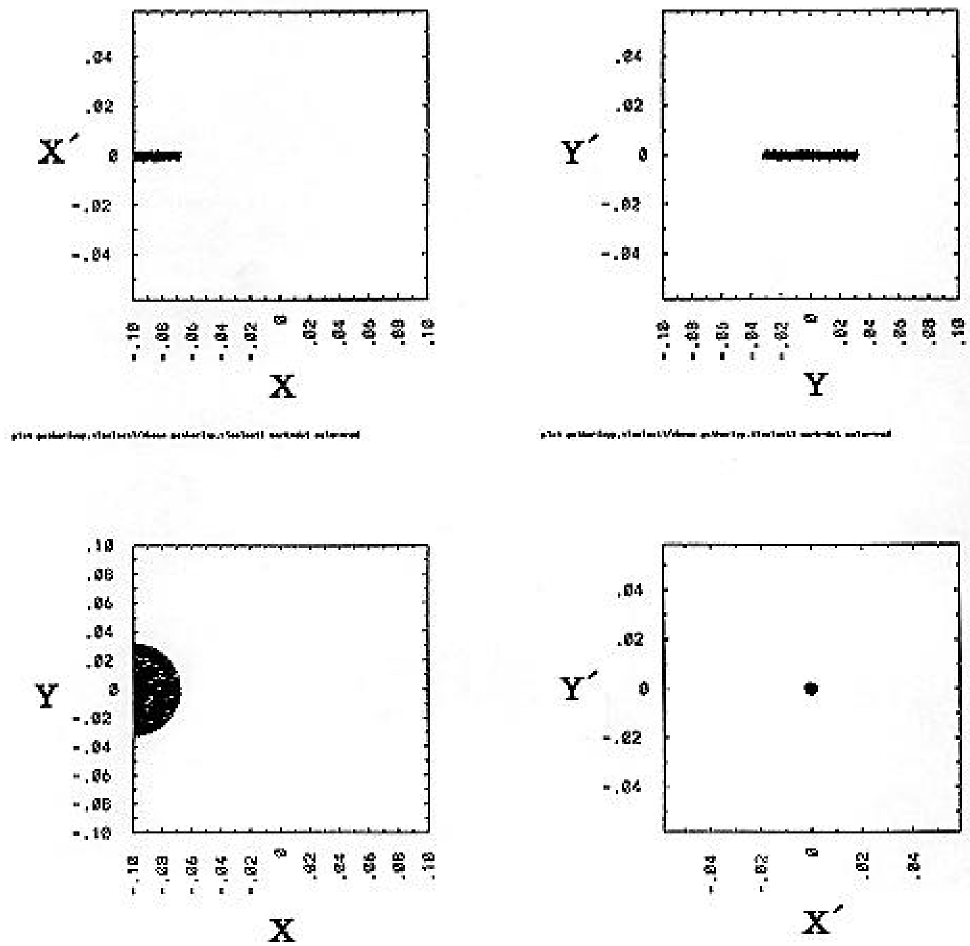
half period = 0.844 m
quadrupole occupancy = 0.5
B' = 50.35 T/m
σ_0 = 70°



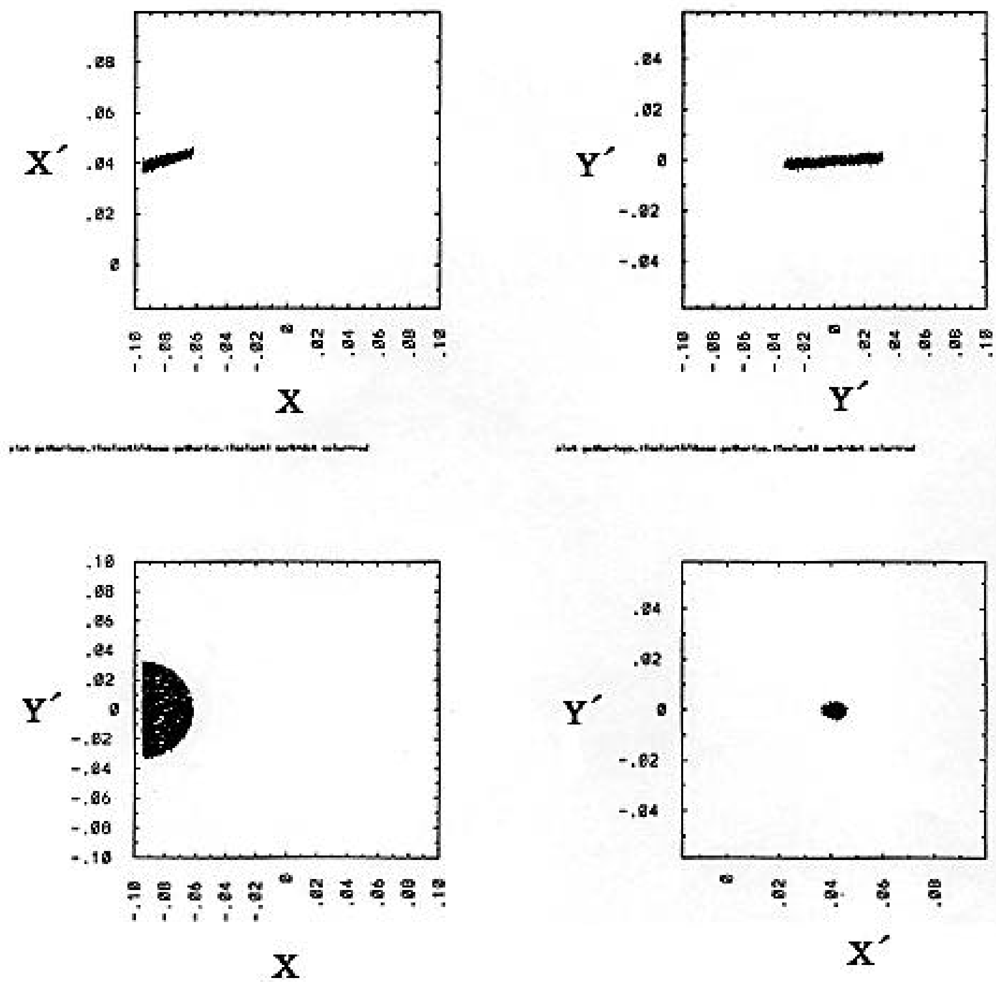
Step 600, T = 0.6464×10^{-6} s, Zbeam = 20.2608 m



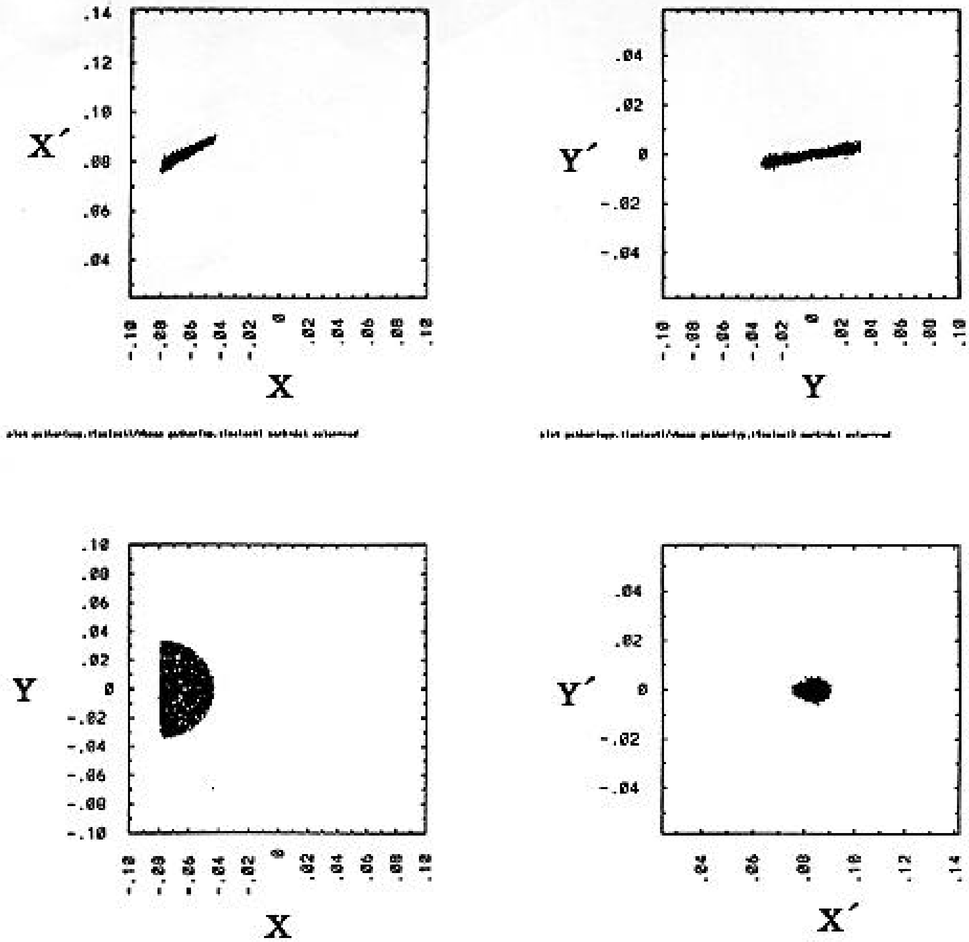
Normalized Y Emittance
pi-mm-mrad
8.0
7.5
7.0
6.5
6.0
5.5
5.0
0
2
4
6
8
10
12
14
16
18
20
Z (m)
z0 = 0.000
A G Transport
End of matching system
End of septum



Step 0. T = 0.0000×10^{-6} s, Zbeam = 0.0000 m

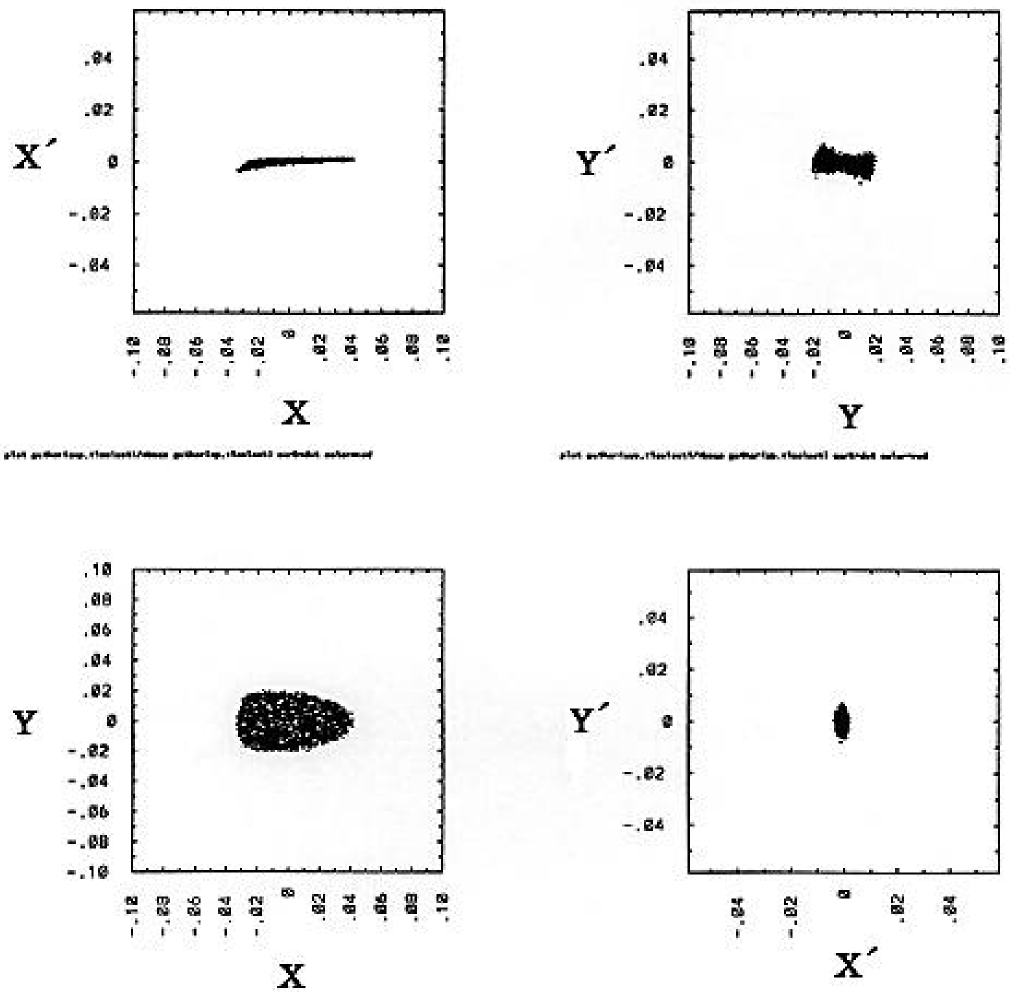


Step 8. T = 0.0086×10^{-6} s. Zbeam = 0.2701 m



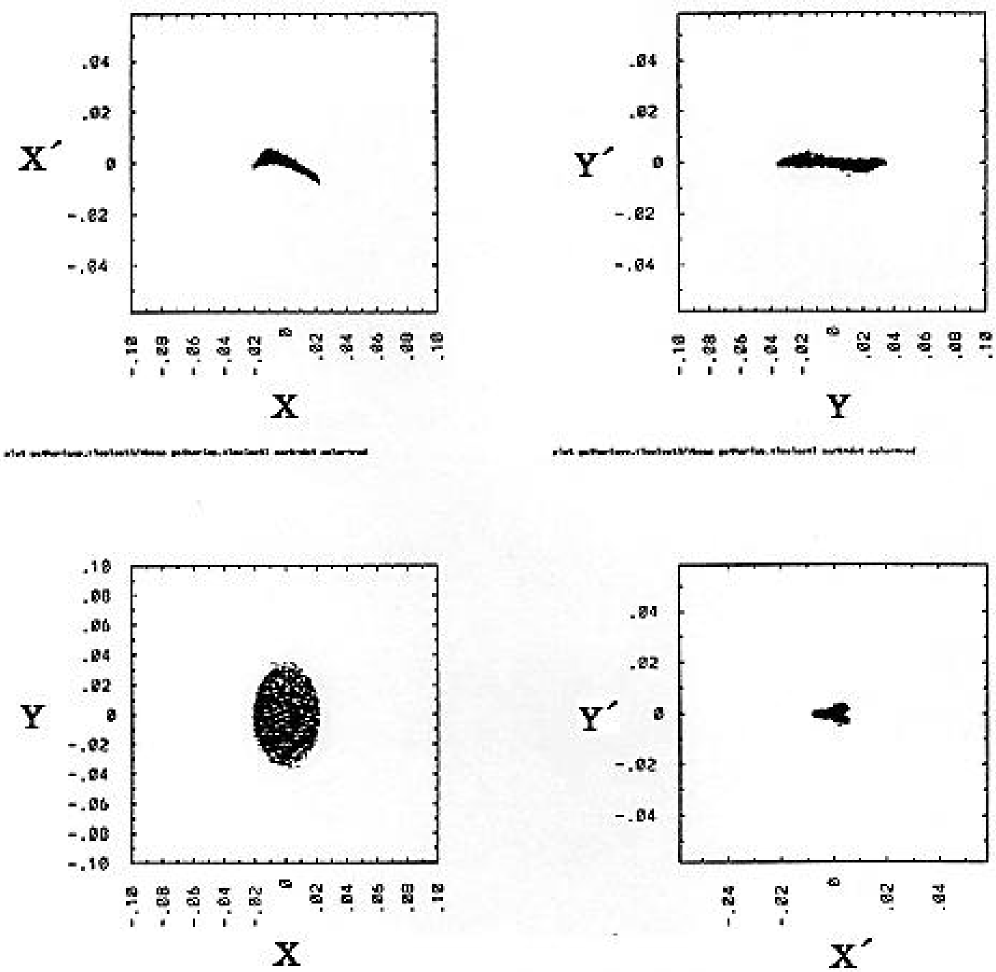
Step 16, T = 0.0172x10^{-6} s, Zbeam = 0.5403 m

CENTER OF 2ND MATCHING QUAD



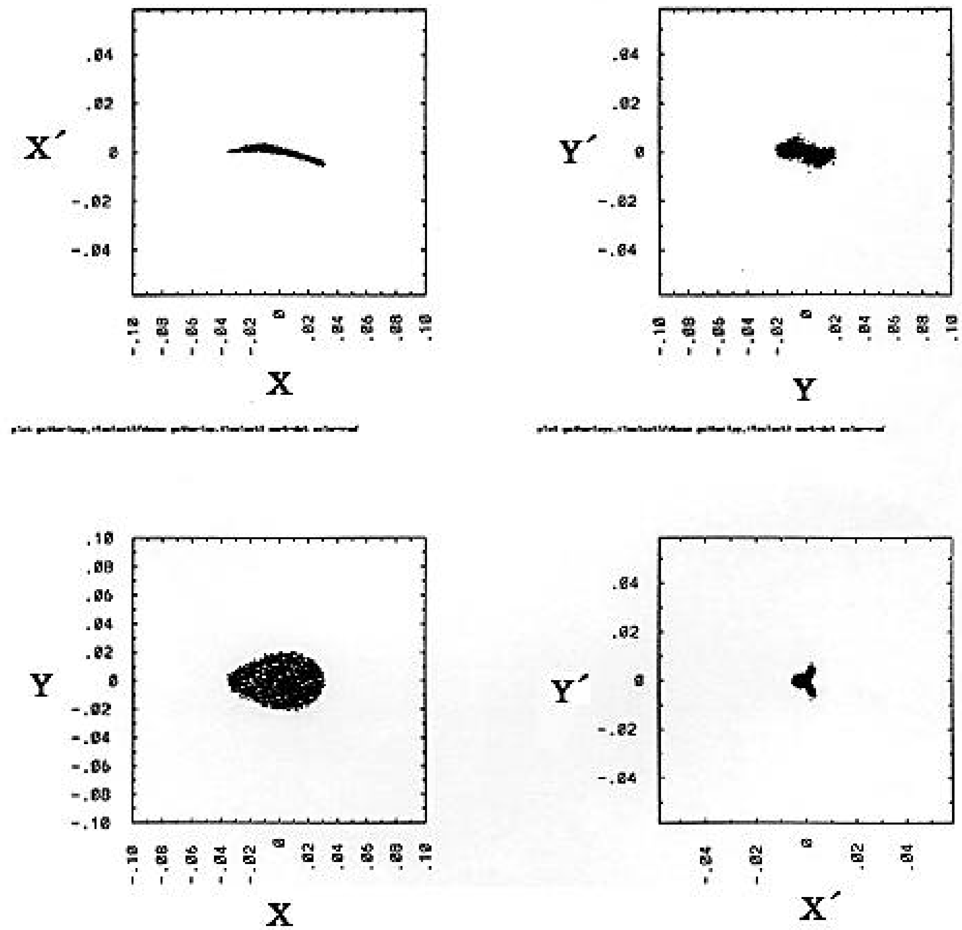
Step 41. T = 0.0442×10^{-6} s, Zbeam = 1.3845 m

CENTER OF 3RD MATCHING QUAD

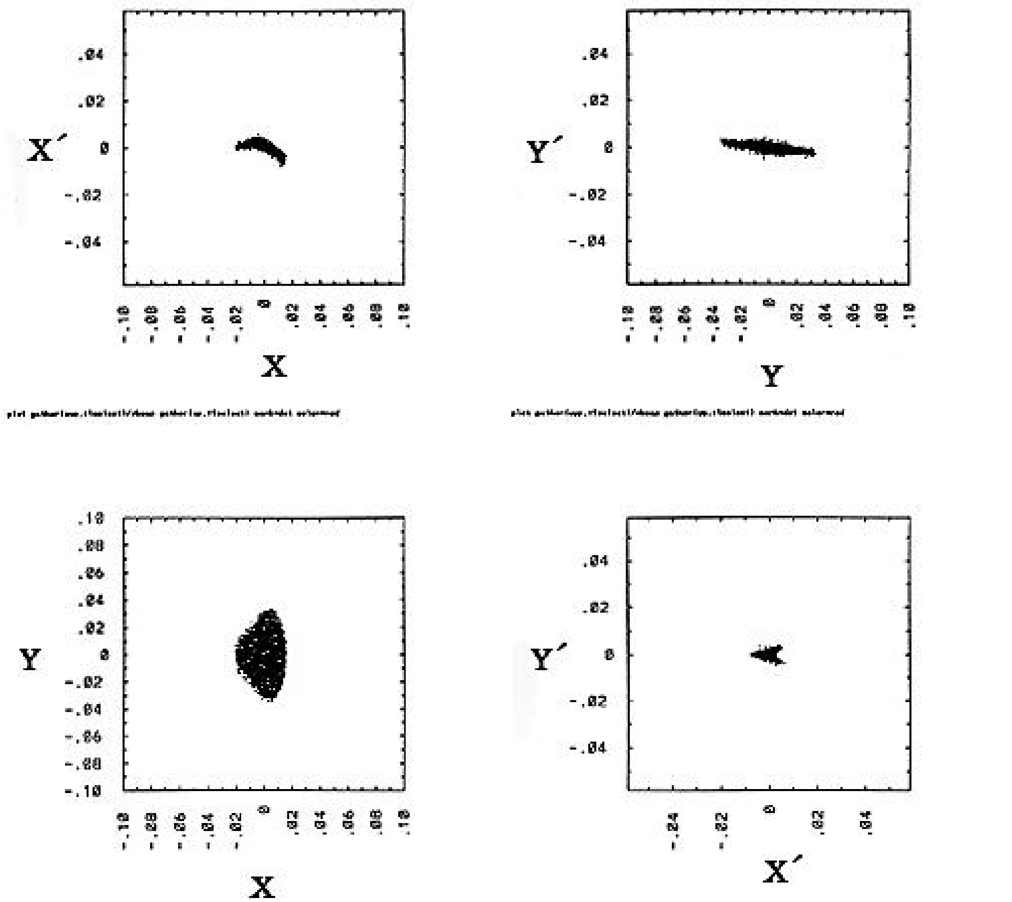


Step 66, T = 0.0711×10^{-6} s, Zbeam = 2.2287 m

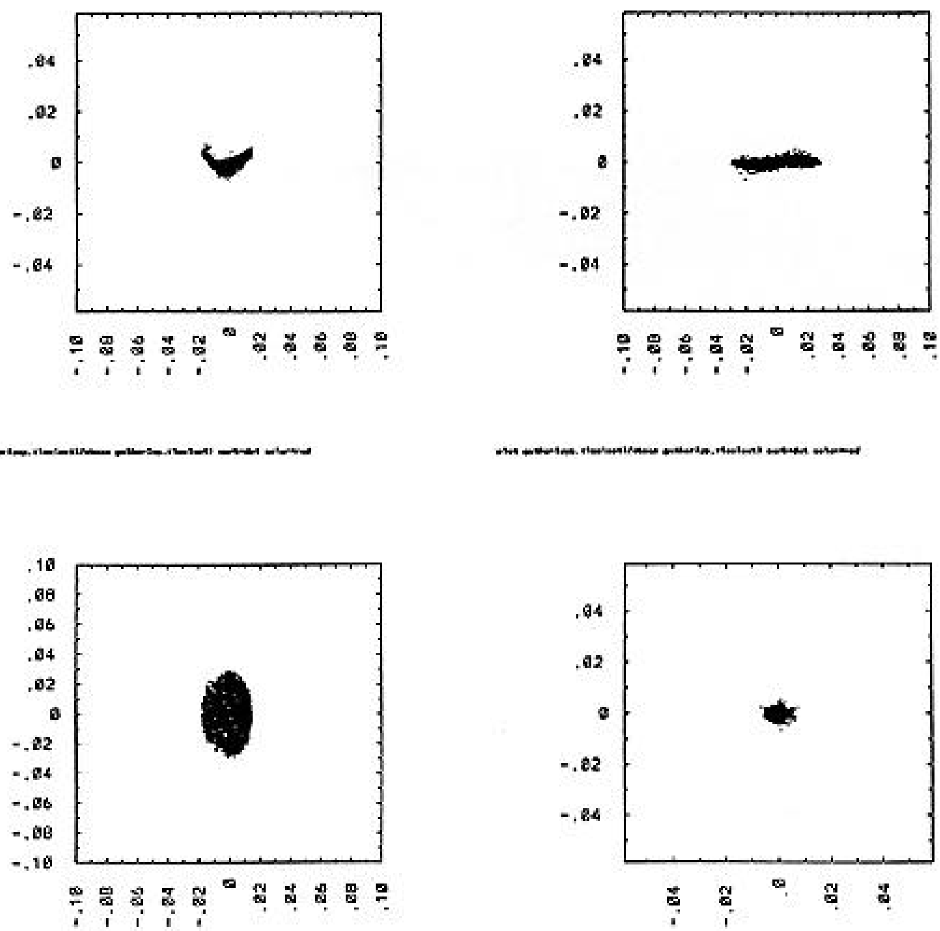
CENTER OF 4TH MATCHING QUAD



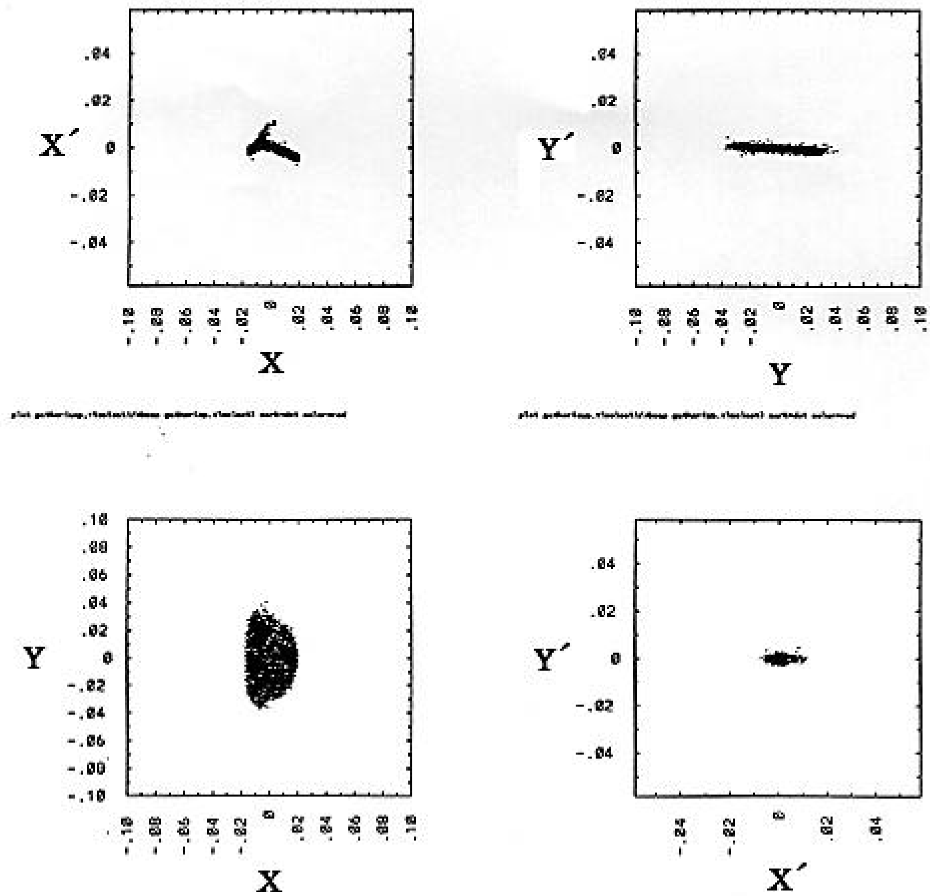
Step 91, T = 0.0980×10^{-6} s, Zbeam = 3.0729 m



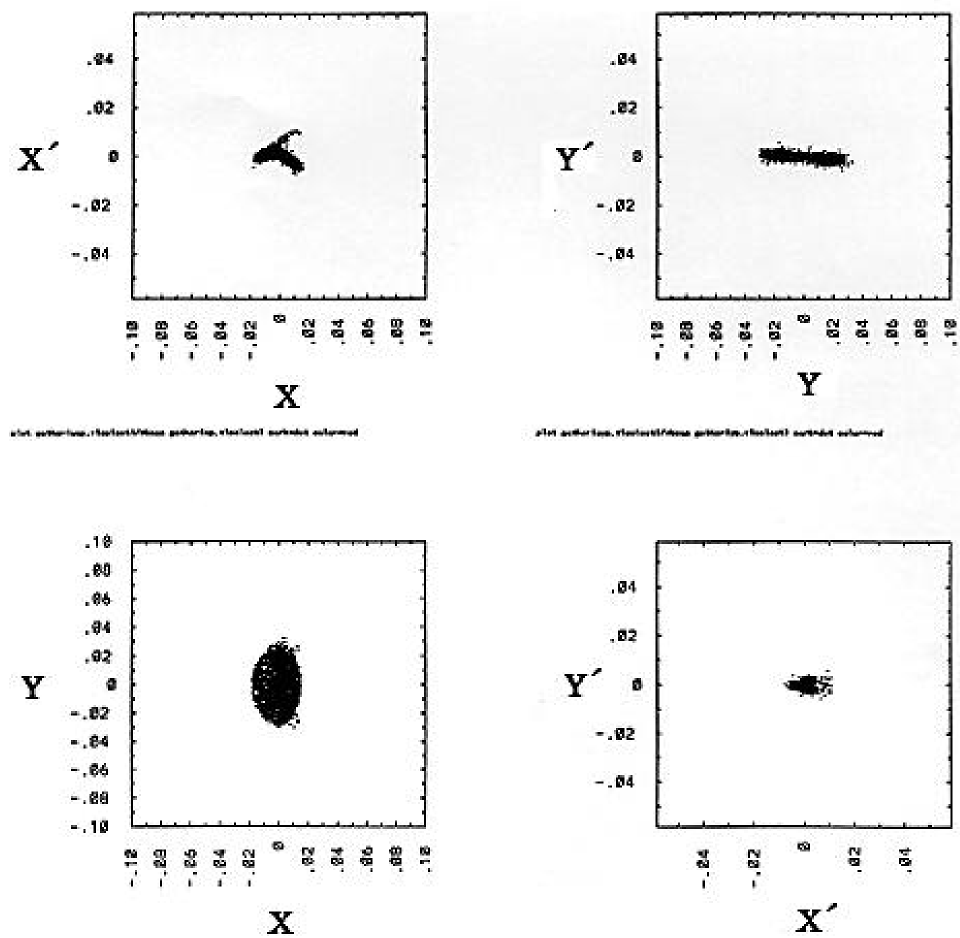
Step 116. T = 0.1250×10^{-6} s, Zbeam = 3.9171 m



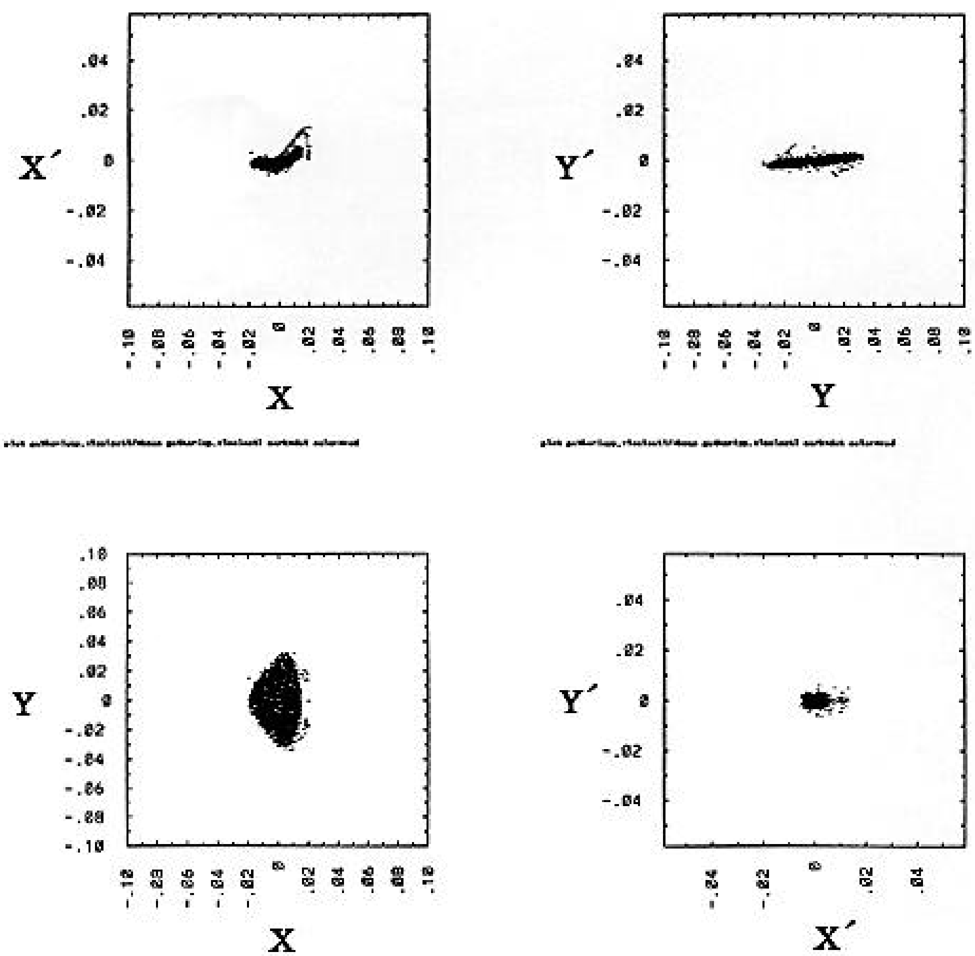
Step 166, T = 0.1788×10^{-6} s, Zbeam = 5.6055 m



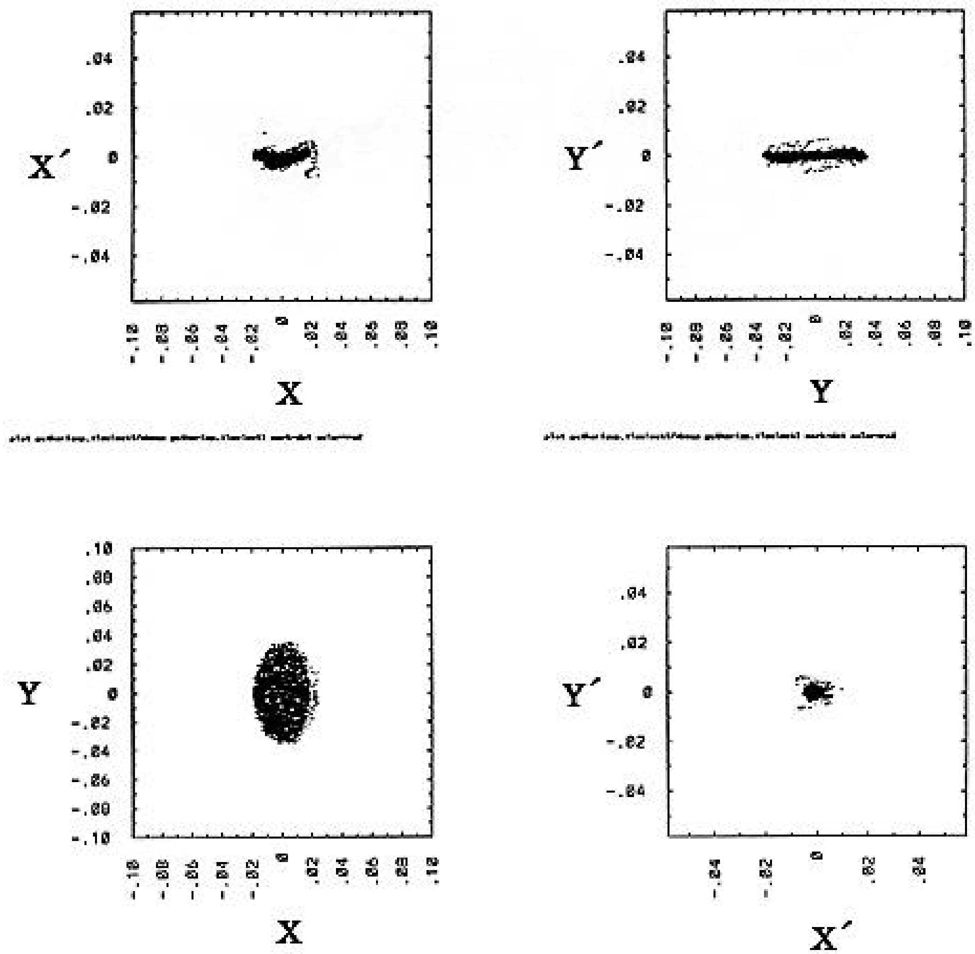
Step 266, T = 0.2866×10^{-6} s, Zbeam = 8.9823 m



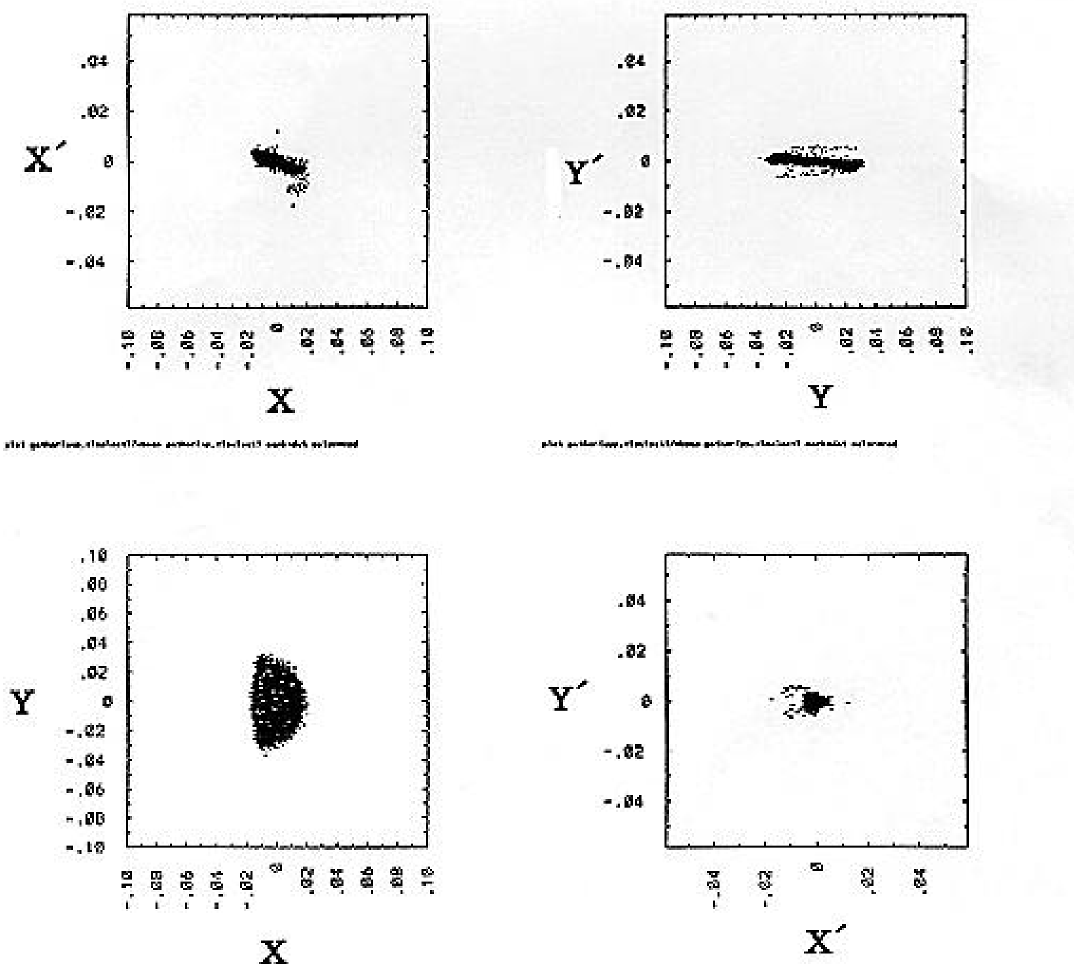
Step 316, T = 0.3404×10^{-6} s, Zbeam = 10.6707 m



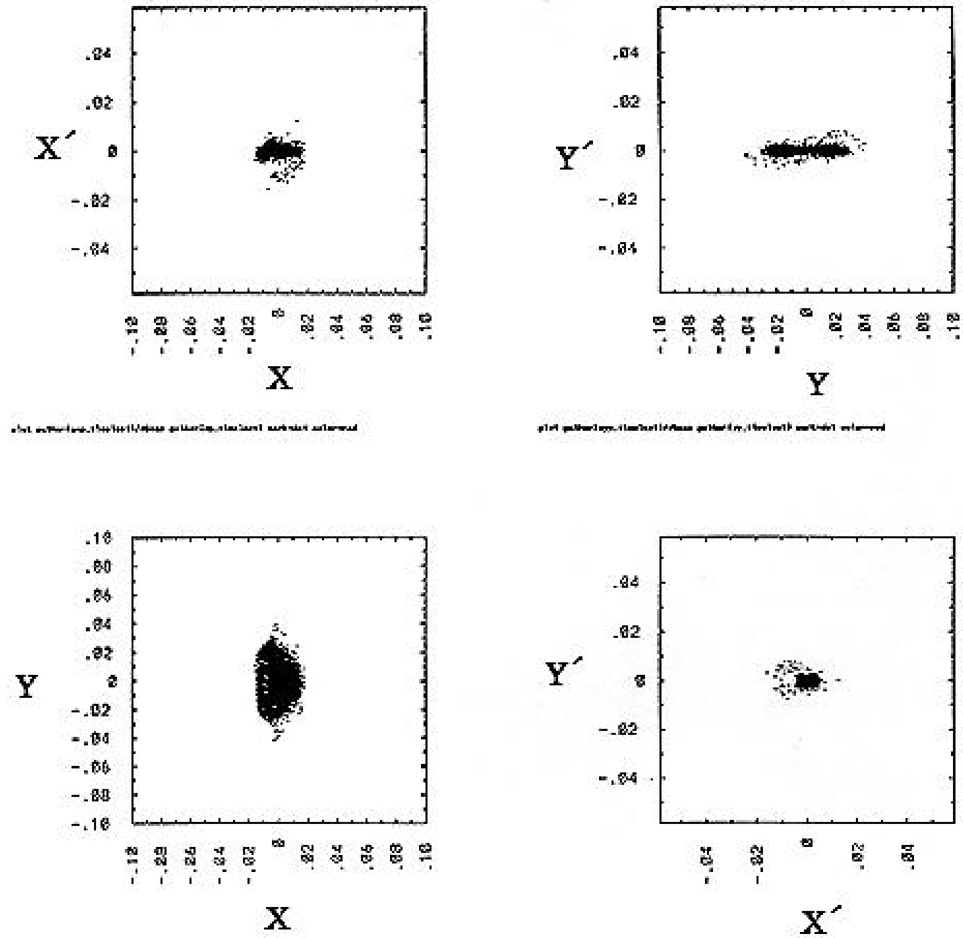
Step 366, T = 0.3943×10^{-6} s, Zbeam = 12.3591 m



Step 416, T = 0.4482×10^{-6} s, Zbeam = 14.0475 m



Step 466. T = 0.5020×10^{-6} s. Zbeam = 15.7359 m



Step 516, T = 0.5559×10^{-6} s, Zbeam = 17.4243 m

Comments on PIC Results

At this point there are many effects left out of the simulations, including fringe fields, and “2D” imperfections of the septum dipole fields. However it is encouraging that there is minimal change in the beam during the actual splitting process. After splitting we are left with a beam which, because of its shape, has significantly nonlinear space charge fields. If the beam is allowed to evolve, a large halo develops.

Future work will concentrate on the use of nonlinear focusing elements (sextupole?) to attempt to “cancel” the effect of the nonlinear space charge forces. We will also look at splitting before drift compression, and at the lower perveances of driver designs, since lower perveance is likely to lead to less emittance growth. It will also be important to evaluate the final beam by passing it through a final focus system and focusing it to a spot.

Status & Conclusions

1. Will the resulting distribution function focus correctly?

Answer: Only preliminary PIC calculations have been done, so the answer is uncertain. There is a significant change in the beam phase space distribution, and space charge forces are quite nonlinear. Nonlinear focusing elements might be useful in reforming an elliptical uniform beam.

2. How much beam will be lost?

Answer: A little over a percent of the beam actually impacts the septum. Sputtered ions will add less than a percent. This amount of loss seems acceptable.

3. Will the beam destroy the septum?

Answer: Yes. Must use an expendable "pseudoseptum" to shield the true current-carrying septum.

4. Will the septum overheat due to i^2R losses?

Answer: No

5. Is the power supply credible?

Answer: It is do-able. The cost may be too high.

6. Will ions sputtered by the head of the beam destroy the beam tail?

Answer: No. They are traveling too slowly to hit more than a percent or so of the beam.

7. What will be the result of electrons coming off the septum into the beam?

Answer: We don't know. This needs careful simulation, and since the electron emission cannot be modelled exactly, simulation must cover a range of parameters. The electrons will be confined to field lines, and therefore will not follow the beam. The septum could also be biased to control them if necessary.

8. Would the pumpout time for sputtered ions limit the machine rep rate?

Answer: This hasn't been studied yet.

9. Is the cost of the system reasonable?

Answer: The cost is not yet known, nor are the benefits of this type of splitting until further PIC exploration has been done.

Acknowledgments

The authors gratefully acknowledge the contributions to this work of Scott Armel, who calculated the range of ions in copper.